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Models and Products

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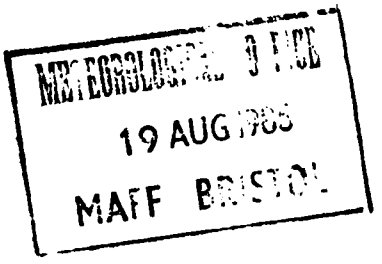

Operational numerical forecasting: models and products

This issue of the *Meteorological Magazine* is devoted to four articles on the Meteorological Office's operational numerical forecasting system. At the core of the system are the 15-level numerical weather prediction models, and these are the subject of the first paper. The second paper deals with the equally important question of the analysis of observations to provide starting conditions for the numerical forecasts. In the third paper attention turns to the dependent oceanographic models, for surface waves and storm surges, which are driven by surface winds and sea-level pressure fields from the atmospheric models. The further processing of results from the models to derive useful output products is the subject of the fourth paper. These products are required both for national purposes and for distribution to other meteorological services in accordance with Bracknell's international roles.

The articles have been prepared by staff in the Central Forecasting Branch of the Meteorological Office, and are intended to provide a survey from an operational viewpoint. The 15-level models and their data assimilation schemes were developed in the Forecasting Research Branch, and the physical parametrizations used in the models were formulated in the Dynamical Climatology and Synoptic Climatology Branches. The reader is referred to the relevant reports prepared in these Research Branches for full details of the various formulations and techniques.

A further four articles, dealing with evaluation and applications of the numerical forecasts, will appear in the next issue of the *Meteorological Magazine*.

The numerical forecasting system described in this issue, built around the 15-level models, has been operational since September 1982. At the time of this publication the system is well established, with a number of earlier problems and shortcomings remedied, and is widely recognized as being highly successful. Nevertheless, further important improvements are currently being researched, and continuing advances in performance may be expected for several years to come.

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The 15-level weather prediction model

By A. J. Gadd

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Summary

The 15-level model is introduced in relation to earlier numerical weather prediction models, and the operational roles of both the global and the fine-mesh versions are outlined. Factors involved in the design of the model are discussed. A brief description is given of the main features of the formulation of the model.

1. Introduction

After research investigations during the 1950s and early 1960s, numerical weather prediction has been used operationally in the Meteorological Office since 1965. A 3-level quasigeostrophic model was used on the KDF9 computer until 1972, when a 10-level primitive-equation model in pressure coordinates was introduced on the 360/195 computer. This 10-level model was used in two forms: for the northern hemisphere north of 15°N with a 300 km grid and for a region near the British Isles with a 100 km grid. The 10-level model was used until 1982 and during its lifetime three different integration schemes were used. In 1978 important changes were made in the model's formulation: a more accurate lower boundary condition was introduced and the effects of radiation were included.

In 1982 a 15-level primitive-equation model in sigma coordinates was introduced on the Cyber 205 computer, and this model is the subject of the present paper.

The 15-level model is used operationally in two versions. There is a global version which is required to fulfil the Office's responsibilities in Defence, as a World Area Forecast Centre for civil aviation (Hardman 1985), in support of marine and other commercial services world-wide, and to provide guidance for medium-range forecasting. The horizontal resolution used is the maximum possible for the original configuration of the Cyber 205 computer, with 1.5° spacing of grid points in latitude and 1.875° spacing in longitude. Global forecasts to 6 days ahead are computed twice daily, from 00 GMT and 12 GMT starting conditions, and with results available by 05 GMT and 17 GMT, and, after the necessary further processing (Francis 1985b), are distributed to other countries in Europe and elsewhere.

A second, regional version of the 15-level model has been designed principally to meet the needs of short-range public service forecasting for the United Kingdom (Hunt 1985) and also to support marine services for the European continental shelf and the Mediterranean Sea (Ephraums 1985). For these purposes the predictions of precipitation, surface wind and the positions of fronts are crucially important, and these predictions are known to benefit from a closer spacing of the grid points. This is achieved within the available computing capacity by using a fine mesh of points (with spacing 0.75° by 0.9375°) over a limited area (80°W–40°E, 30°N–80°N). At the lateral boundaries of this region the calculations make use of information provided from integrations on the global grid. Forecasts to 36 hours ahead are computed twice daily, with results available by 03 GMT and 15 GMT, and are distributed internationally for use in most of the nations within the region of coverage. The surface wind forecasts are particularly valuable for input to wave and surge prediction models (Francis 1985a).

The progression of models over the years reflects the scientific advances in numerical weather prediction and the increasing capacity of the computers available. Thus the 15-level model is based on what are currently judged to be the best available treatments of the relevant physics and mathematics, whilst its operational use is made possible by the availability of the powerful Cyber 205 computer.

Along with the progression of modelling techniques there has been an expansion of the area of coverage. This process was completed within the implementation of the global version of the 15-level model. However, as noted above, regional modelling is still important in that it permits a higher horizontal resolution, in a limited area of special interest, for a given computing capacity.

A parallel historical development may be noted in the methods used to provide initial data for the numerical models. The 3-level model required objective analysis of the height field. The 10-level model required objective analysis of the height and humidity fields, but its initial wind values were diagnosed from the height analysis using the balance and omega equations. The 15-level model uses analysis and data assimilation of potential temperature, surface pressure, relative humidity and wind component data derived from observations to obtain initial fields of these variables in sigma coordinates (see the companion paper by Atkins and Woodage 1985). This system has its origins in work carried out as part of the Office's contribution to the Global Weather Experiment in 1979.

The increasing skill of numerical forecasts during the course of this historical development may be seen in sequences of verification statistics (Flood 1985).

2. The design of the 15-level model

The design of the 15-level model was based on research which compared alternative techniques (Cullen *et al.* 1981). During the lifetime of the 10-level model, three different methods for the numerical integration of the primitive equations had been used (Gadd 1978a), each one improving on the efficiency of its predecessor. Changes had also been introduced to improve the accuracy of the finite-difference approximations (Gadd 1978b). It was found that the numerical techniques used in the 10-level model at the end of its development were more efficient than, and equal in accuracy to, the alternatives and so were largely retained. On the other hand the representations of precipitation, convection, boundary-layer turbulence and radiation for the 15-level model were derived from earlier work in the Office on general circulation modelling and climate research (Lyne and Rowntree 1976, Richards 1980, Corby *et al.* 1977). The original formulation of the 15-level model was described in full by Dickinson and Temperton (1984); further improvements are constantly being researched and are introduced operationally as soon as they are sufficiently proven.

At a time when several global modelling centres around the world have changed over to spectral models, some comment is appropriate on the retention of finite-difference methods in the 15-level model. The choice between spectral and finite-difference models is essentially an economic one, there being no intrinsic difference in the quality of result that may be obtained with either approach. In some centres greater accuracy has been obtained in synoptic-scale forecasting with a given computing power by using a spectral model. However, the efficiency and accuracy of the numerical techniques used in the 15-level model are such that it is unlikely that any economic advantage could be obtained using a spectral version. Also important in the context of the Meteorological Office's requirements is that exactly the same finite-difference formulation, indeed the same coding in large measure, can be used in both the global model and the limited area fine-mesh model. Finally, it should be noted that the balance of economic advantage shifts towards finite-difference models when it comes to sub-synoptic features, especially fronts, and this may become more important with the trend to higher and higher resolutions in global models.

3. The grids

In the vertical the sigma (σ) coordinate system is used, where σ is pressure (p) normalized by surface pressure (p_*). Thus the coordinate surfaces follow the shape of the model's orography (grid-scale mean values). The distribution of the 15 levels is shown in Fig. 1. In the mid-troposphere the vertical resolution

is about 100 mb, but near jet-stream levels there is a higher resolution of about 60 mb. A high vertical resolution is provided in the atmospheric boundary layer, with the lowest level approximately 25 m above the surface. The uppermost level is about 25 km above the surface. The 15 levels, at which all the model variables except vertical velocity are calculated, may be regarded as the midpoints (by log σ) of 15 layers of air. The vertical velocity ($\dot{\sigma} = D\sigma/Dt$) is calculated at the layer boundaries. The boundary condition $\dot{\sigma} = 0$ is applied at the earth's surface ($\sigma = 1$) and at the upper boundary of the uppermost layer.

The horizontal grids are defined using spherical polar coordinates ϕ (latitude) and λ (longitude). With grid spacing $\Delta\phi = 1.5°$ and $\Delta\lambda = 1.875°$, the global model has 121 points from pole to pole and 192 points around each latitude circle. The fine-mesh model has a double resolution over its limited area of coverage. In both cases there is a staggering of model variables in the horizontal in an arrangement known as the B-grid and illustrated in Fig. 2. Thus the 121×192 (= 23 232) points of the global grid form the corners of grid boxes. At these corner points the surface pressure (p_*), potential temperature (θ) and humidity mixing ratio (q) are predicted, whilst the geopotential (Φ) and vertical velocity ($\dot{\sigma}$) may be diagnosed. The horizontal velocity components (u, v) are predicted at the centres of the grid boxes. Special procedures are adopted at the poles.

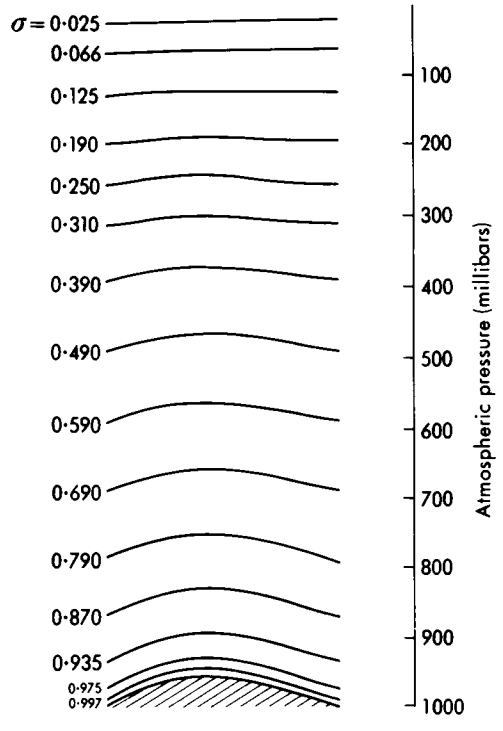

Figure 1. Sigma levels of the 15-level model.

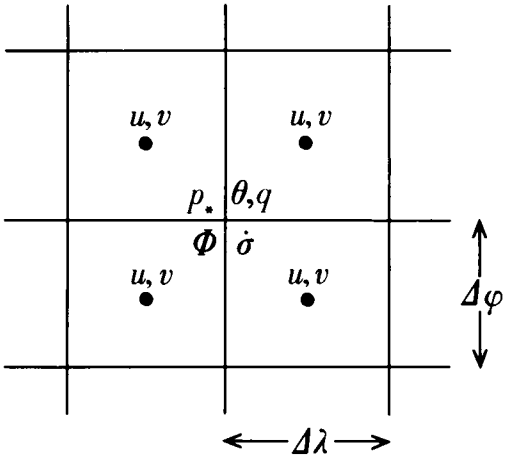

Figure 2. The arrangement of variables on the B-grid.

4. Dynamical and numerical formulation

The primitive equations are used in advective form, and are integrated using the split explicit integration scheme. This includes a modified Lax–Wendroff method for horizontal advection and a forward–backward scheme, with trapezoidal integration of the Coriolis terms, for the gravity–inertia

adjustment stage. The time-step for the integration of the advection terms is three times that for integration of the gravity–inertia terms. The forward–backward scheme includes special features to prevent the spatial lattice separation that can be a problem with the B-grid.

In high latitudes the small east–west separation of the grid points would impose unacceptable restrictions on the time-steps allowed for computational stability if special measures were not taken. Thus stability filtering is applied as necessary in the east–west direction to allow the use of time-steps (15 minutes in the global model and $7\frac{1}{2}$ minutes in the fine-mesh model) governed by the north–south grid spacings. In the global model, Fourier analysis is used around latitude circles and short-wavelength components of the fields are damped using coefficients calculated for each line of latitude and for each forecast, taking account of the maximum wind speed present. Thus the region of filtering extends further towards the equator in a winter hemisphere than in the corresponding summer hemisphere. Where stability filtering is needed in the fine-mesh model, a multipoint filter (25 points) is applied along lines of latitude to provide an approximation to Fourier damping.

5. Parametrizations

As in all modern numerical models of the atmosphere, the parametrization of physical and sub-grid-scale processes is an important aspect of the formulation of the 15-level model. In principle, the parametrizations currently available are used in the same way both in the global and in the fine-mesh versions of the model. However, it is sometimes necessary or desirable to introduce changes first in one version and later in the other.

The current parametrizations are as follows:

(i) *Large-scale precipitation*, including the ice phase and the evaporation of precipitation as it falls.

(ii) *Convection*, producing a redistribution of heat and moisture in the vertical (and convective precipitation where appropriate) and based on parcel theory, modified by entrainment, and detrainment.

(iii) *Surface exchanges and boundary-layer turbulence*, exchanging heat, moisture and momentum among the four lowest model layers and with the surface.

(iv) *Radiation*, including the diurnal cycle of solar radiation, and interactive with temperature and humidity and with cloud inferred from humidity.

(v) *Gravity wave drag*, applied at upper levels, but calculated from low-level wind and static stability and the variance of orographic height within each grid box.

(vi) *Horizontal eddy diffusion.*

(vii) *Vertical eddy diffusion*, at low latitudes only.

The calculations of surface exchanges require values of a number of surface parameters. The distributions of sea-ice and snow cover are specified climatologically. Over open sea the surface contact temperature is analysed every day using ship, buoy and satellite measurements, and is held constant during each forecast. Over land and sea-ice the surface contact temperature is predicted using calculated components of the surface energy balance. Specifications are also required of albedo, soil moisture and effective thermal capacity.

6. Lateral boundary conditions for the fine-mesh model

The advantages available through the higher horizontal resolution of the fine-mesh version of the 15-level model are contingent on an adequate method for updating the lateral boundaries during the course of the forecasts. Theoretical investigation of this problem for the primitive equations has shown

that a mathematically satisfactory method is very difficult to devise. Fortunately a number of pragmatic schemes exist which work adequately well in operational practice, and one of these is used for the 15-level model.

The method that is used involves a complete overspecification of the boundary conditions in that the tendencies of all predicted variables at all boundary points are externally prescribed. These tendencies are derived from values output at hourly intervals from suitable global or hemispheric integrations on the coarser grid and are used to update the fine-mesh boundaries every time-step. An enhanced diffusive damping is used at all grid points within 3 gridlengths of a boundary. Within this boundary zone the coefficients of the non-linear horizontal diffusion formulation are enhanced by a factor of 3 compared with their values in the interior regions.

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Observations and data assimilation

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Summary

Initial fields for the 15-level model are provided by a data assimilation scheme. Conventional and satellite observations of relevant meteorological quantities are processed to provide 'observed' values of model variables. Global analyses are produced at 6-hourly intervals, 00, 06, 12 and 18 GMT, using data valid within 3 hours of each of these times. This is achieved by assimilating the processed observations into the 6-hour forecast from the previous analysis, using univariate optimum interpolation to provide corrections at the model grid points and additional damping to control unwanted high-frequency oscillations. Initial fields for the regional (fine-mesh) model are provided by a fine-mesh assimilation scheme. Analyses are produced at 3-hourly intervals by assimilating observations valid within 1½ hours of the analysis time into the regional model. The fine-mesh assimilation is restarted every 12 hours by interpolation from a global assimilation.

1. Introduction

A necessary condition for a numerical model of the atmosphere to produce a good forecast is that the initial values of the model variables should be well specified. They should properly represent all the features, which can be resolved by the model, present in the atmosphere on a given occasion, and they should not contain imbalances between the variables which would excite spurious oscillations in the subsequent forecast. At the Meteorological Office a data assimilation scheme is used to provide initial conditions for both the global and regional versions of the 15-level model described in the companion paper by Gadd (1985). The scheme has been designed to use as much as possible of all available data, both conventional observations reporting at synoptic hours and satellite and aircraft observations which may report at any time. Before observations can be assimilated into the model they have to undergo quality control and be processed into a suitable form.

2. Observations

Meteorological data consist of measured or derived variables at different levels in the atmosphere, recorded at various times of the day and night. Several different kinds of observation are reported: traditional types are the surface and radiosonde reports which give excellent data coverage at synoptic hours over the land masses and major shipping routes. However, there are some parts of the northern hemisphere and vast areas of the tropics and southern hemisphere where these observations are not available, and it is in such regions that the satellite data have been most beneficial, providing asynoptic observations evenly distributed over the whole globe. Also available, along the major airline routes, are aircraft reports which are particularly useful to the United Kingdom in providing data across the Atlantic.

All observations are transmitted in coded form on the Global Telecommunication System (GTS) and are received at Bracknell by the Telecommunications Branch. From there they are routed to other users (e.g. outstations), as well as being passed to the Meteorological Office IBM computer where they are decoded and stored in the Synoptic Data Bank. At this stage some basic quality control is performed (such as checking reported values against climatological limits and testing radiosonde ascents for internal consistency) and an indicator or 'flag' is set against any datum suspected of being in error. As the observations come in they are monitored by forecasters in the Central Forecasting Office (CFO) who examine the data together with departures from model fields using visual display units. The forecasters

also analyse charts of plotted data at four main levels (surface, 500 mb, 250 mb and 100 mb), and these are considered to be the best available estimate of the state of the atmosphere at the synoptic hours. At this stage forecasters are able to 'intervene', rejecting any data suspected of being erroneous, and inserting 'bogus' or artificial data in areas where observations are sparse and model fields are considered to be poor.

The data assimilation scheme will be described in detail in the second part of this paper, but it is necessary to note here that it requires values of potential temperature (θ), westerly and southerly wind components (u and v), relative humidity (U) and model surface pressure (p_*). All observed data must be presented in the form of these variables in order to be used. Some types of data require only a simple change of variable using a standard formula: examples are the conversion of vector winds to wind components, the conversion of dew-point and temperature to relative humidity, and the conversion of temperature to potential temperature. However, other calculations could be carried out in a variety of ways using different approximations and assumptions, and each method gives a slightly different result. It is very important that the data passed to the model should be as accurate as possible, and that no biases should be introduced. It is equally important that the pre-processing should be carried out efficiently, as any time wasted at this early stage in the operational suite will cause unnecessary delay of the forecast products. A satisfactory balance must be found between the cost incurred and the accuracy attained in choosing methods of pre-processing the data. The methods used for the Meteorological Office 15-level model will now be described.

Surface observations

Surface observations comprise reports from land stations, ships and drifting buoys. These typically provide values of surface temperature, dew-point, wind, and mean-sea-level (msl) pressure. Exceptions to this are drifting buoys, which report msl pressure only, and high-level land stations where the derivation of msl pressure from the (measured) station-level pressure would be unreliable. In this case other variables are reported, such as station-level pressure or the geopotential of a standard pressure level. Surface temperature data are not used in the model, as local anomalies are likely to render them unrepresentative of the atmosphere on the scale of the model grid. For the same reason, surface wind and humidity data are not used over land, although they are used over the sea. The most important data derived from surface observations are values of model-surface pressure (p_*). Where the model orography has the same geopotential as that of the reported pressure (e.g. over the sea), no calculation is necessary as p_* is equal to the reported pressure. However, for most land stations some extrapolation is required, and assumptions must be made about the temperature structure in the layer in order to derive p_*. The best that can be done is to use model values, and ensure that the method adopted is consistent with that used to convert model p_* values to msl pressure for chart output. The calculation is done using the hydrostatic equation integrated assuming a constant lapse rate within the layer. The lapse rate chosen is the ICAO (International Civil Aviation Organization) standard value (6.5 K km^{-1}) and a reference temperature is obtained at the model surface by extrapolating from a level above the model boundary layer (about 800 mb). This method ensures that where msl pressure data are equal to the model output values, no change will be implied in p_* when the data are analysed.

Radiosonde data

Radiosondes provide values of temperature, dew-point and wind at significant levels of the ascent, together with geopotentials of the standard pressure levels. The number of levels reported varies according to the complexity of the atmosphere and the height attained by the sonde balloon, but is typically between 40 and 80. The temperature, wind and humidity data are too numerous to be passed to

the analysis at the reported levels, as the vertical detail could not be resolved by the model. It is therefore necessary to condense each ascent to a representative set of data at levels approximating to those of the model. This is achieved by using all reported values, weighted linearly in log pressure, to calculate mean values of each variable over layers centred on model levels. This has the effect of smoothing out extreme features such as maximum winds and tropopause temperatures which cannot be explicitly resolved by the model. The method is consistent with the assumptions made when output charts of standard-level values are produced, and ensures that geopotential (the main variable used for assessment by forecasters) is accurately represented.

The reported values of standard-level geopotential are not used directly in the model, but for some years statistics have been collected on the differences between observed and analysed 100 mb geopotentials. These are used to identify systematic differences between sondes and to derive appropriate corrections which are given in terms of 100 mb geopotential. In order to use this information in the model, equivalent temperature corrections are derived which are added to the σ-level values passed to the analysis.

Satellite temperature soundings

Temperature soundings are derived from radiance data measured by the polar orbiting satellites. Temperature and humidity mixing ratio are the variables initially derived, but these are converted to thickness (or layer mean virtual temperature) and precipitable water content (PWC) for standard layers, before they are transmitted on the GTS. Since the Meteorological Office model does not analyse these variables, it is necessary to invert the calculations carried out before transmission to reconstruct the original data as accurately as possible. This is done by converting to layer mean temperatures, using the PWC data to make the correction from virtual to true temperatures. The PWC data are not used directly as humidity observations as the errors are rather large, particularly for higher latitudes. For soundings made in cloudy conditions it is not possible to obtain humidity data. The method used to derive thicknesses for transmission in these cases is very complicated and could not be inverted operationally. A simple approximate method is used instead, with a relative humidity of 80% being assumed to carry out the conversion of virtual to true temperature.

Although the soundings transmitted on the GTS provide excellent coverage of temperature data, they are currently available only at spatial intervals of about 500 km (or 250 km in a compressed format) and are received at Bracknell 3 hours or more after the radiance data are recorded. They are valuable for the global coarse-mesh model, but are of limited use for the fine-mesh model which has a resolution of about 75 km and runs operationally 2 hours after data time. For this reason the Satellite Meteorology Branch has developed a system for receiving the radiance data directly from the satellite as it passes over the United Kingdom, and performing the processing locally to provide temperature data directly with a horizontal resolution of about 80 km, typically within 1 hour of being recorded. This processing system is known as HERMES (High-resolution Evaluation of Radiances from Meteorological Satellites) and experiments are being carried out to determine the best way to use these data in the models.

Satellite cloud-track winds

Wind data are derived from observations of movements of clouds at various levels in the atmosphere, recorded by the geostationary satellites which constantly view the same area of the globe. The data are transmitted in the form of a wind with an associated pressure, and can be used directly in the model. There are certain errors inherent in these data, owing mainly to the difficulty in estimating the level of the cloud. However, they provide valuable information in tropical areas where other observations are sparse.

Aircraft reports

Aircraft reports contain values of wind and temperature together with the flight level, position and time of observation. Observations are made every 5° or 10° of longitude along the flight path, and also at certain specified reporting positions. Before the data are used in the model they are checked to eliminate any duplicate or conflicting reports from the same aircraft. Winds and temperatures are passed to the analysis at the pressure level equivalent to the flight level. The conversion of flight level to pressure is carried out using equations based on the ICAO standard atmosphere (see World Meteorological Organization 1966).

Artificial observations

Artificial or 'bogus' observations are generated by forecasters in CFO to change the model fields, generally in areas of sparse data where they may have a better idea of the true state of the atmosphere from continuity, experience, or from data unavailable to the model (e.g. satellite pictures). The bogus observations comprise values of msl pressure, geopotential, wind and humidity at the main analysed levels. The geopotentials must be converted to temperatures, and the method adopted is to use model values to calculate the thickness change over each layer implied by the bogus data. The thickness changes are then converted to temperature increments, which are added to the existing model temperature profile to create a complete bogus ascent. The bogus data are treated by the analysis in the same way as any other conventional observations, but are given a higher weight to encourage the analysis to fit them.

3. Data assimilation

Many of the observations described in the preceding paragraphs may be valid at any time during a 24-hour period. The maximum number of conventional observations are still received for 00 and 12 GMT, this being the time at which most upper-air observations are made. For this reason forecasts still start from an analysis valid at those times. However, significant numbers of both surface and upper-air observations are received for 06 and 18 GMT and reports valid at any time are received from satellites, aircraft and drifting buoys. Data assimilation schemes are designed to make the best use of all this information, in particular, to use information valid at all times of the day to produce the best possible analysis valid at 00 or 12 GMT from which to start a forecast.

At the Meteorological Office, this is achieved by producing a global analysis at 6-hourly intervals, 00, 06, 12 and 18 GMT. All observations valid within 3 hours of each of those times are used to modify a 6-hour forecast starting from the previous analysis. Information from observations valid at all previous times is thus carried forward to the current analysis in a process analogous to the use of continuity charts in subjective analysis. The prognostic variables of the forecast model are potential temperature (θ), westerly and southerly wind components (u, v), humidity mixing ratio (q) and surface pressure (p_*). These are carried on a latitude/longitude grid in the horizontal and 15 levels in the vertical defined in terms of terrain-following sigma coordinates (described in the companion paper by Gadd (1985)). The analysis is performed directly in the model variables (except that U is used rather than q because of advantages for quality control) on a grid identical to that of the forecast model, except that the number of points per latitude circle decreases polewards of 50° to maintain a quasi-uniform spacing. Observations must therefore first be processed (as described in the previous section) to provide data in terms of the analysis variables, but not necessarily at model sigma levels.

Quality control

Univariate, three-dimensional statistical interpolation (sometimes known as optimum interpolation) is used in the analysis to interpolate from the observation points to the grid points. However, before this process is carried out, observations are subjected to quality control making use of the same technique. As a first step the observations are checked against the 6-hour forecast from the previous analysis, and when the difference exceeds a criterion dependent on the characteristic error of both the observations and the forecast, the observation is flagged. In the second step, each observation (including those that have been flagged) is checked by comparing it with a value interpolated from the surrounding unflagged observations, again using statistical interpolation. If the difference exceeds a second criterion, which depends on the characteristic error of the observation and the interpolation error (which may be determined from the method of statistical interpolation), the observation is rejected. Observations which fail the first check may be reinstated if they pass the second check, i.e. observations which differ significantly from the 6-hour forecast field may be retained if they are supported by other observations.

Statistical interpolation

Observations which pass the quality control checks (including those performed within the Synoptic Data Bank and the manual monitoring of the Central Forecasting Office) are used to interpolate values of each of the variables at the analysis grid points. Interpolation is actually carried out in terms of the departure of an observation from the model field to give an increment or correction to the model field at each of the grid points, according to equation (1),

$$\Delta\psi_g = \sum_i w_i \left(\psi_i^{\text{observed}} - \psi_i^{\text{model}}\right), \qquad (1)$$

where ψ_i^{observed} is an observation of one of the variables, θ, u, v, U, p_*,

ψ_i^{model} is the model value of the same variable interpolated to the observation point,

$\Delta\psi_g$ is the correction or observational increment for the variable ψ at the grid point,

and w_i is the weight given to observation ψ_i observed.

The summation is taken over a maximum of seven observations of the given variable surrounding the grid point in three dimensions. The weights w_i are determined by minimizing the interpolation error over a large number of cases. They may then be expressed as a function of the pre-specified characteristic errors of the observations and model field, and the 3-dimensional spatial distribution of the observations around the grid point. The displacement time of the observation from the analysis may be taken into account by modifying the observational error.

Assimilation

In the most common method of applying statistical interpolation, the model field is the 6-hour forecast and the whole of the correction $\Delta\psi_g$ is added to this field to produce the analysis. The technique is usually applied in a more sophisticated form than that described above so that, for example, observations of wind may affect a height analysis, and vice versa, through the geostrophic relationship. However, even when such a sophisticated multivariate scheme is used, the simple correction of a 6-hour forecast by an interpolated increment will excite spurious high-frequency oscillations in a subsequent

forecast. These oscillations are caused by small errors in the analysis which result in imbalances between the mass and wind field and unrealistic values of the divergent component of the wind. They produce a noisy forecast and, more seriously, dissipate much of the information from the observations present in the analysis. The usual technique for overcoming this problem is to apply some kind of initialization. The grid-point values of the model variables are adjusted to satisfy certain mathematical constraints which remove the high-frequency oscillations while at the same time ensuring that the values remain close to the observations. The most popular form used today is non-linear normal mode initialization.

At the Meteorological Office an alternative approach is used. The observations are assimilated into the model during the 6-hour forecast preceding the analysis time. First the interpolation weights w_i are calculated using values of the model forecast error appropriate to a 6-hour forecast. Then at each time-step of the 6-hour forecast preceding the analysis, increments are calculated at each of the grid points from differences between the observations and the current model state using the predetermined weights, by means of equation (1). However, only a small proportion (λ) of these increments is added to the model field. This process is represented in equations (2) to (4). Let one time-step of the model be represented by equation (2)

$$\Psi^*_{t+\Delta t} = \mathrm{M}(\Psi_t), \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where Ψ is now a vector representing all the model variables and M is an operator representing one time-step of the model. $\Psi^*_{t+\Delta t}$ is the value of the forecast without assimilating any data. It is then modified by the observations according to equation (3),

$$\Psi_{t+\Delta t} = \Psi^*_{t+\Delta t} + \lambda \Delta \Psi_{t+\Delta t}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where $\Delta\Psi_{t+\Delta t}$ is a vector representing increments at the grid points interpolated from the observations for all variables at time $t + \Delta t$. For any variable, ψ, at a grid point

$$\Delta\psi_{t+\Delta t} = \sum_i w_i \left(\psi_i^{\text{observed}} - \psi^*_{i,\,t+\Delta t}\right). \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Equation (4) is the same as equation (1) with a slight change of notation. λ increases linearly from 0 to 0.35 during the 6-hour period, so that only small changes are made to the forecast fields. This process is illustrated schematically in Fig. 1. For humidity, the model field ($\Psi^*_{t+\Delta t}$) is converted from humidity mixing ratio to relative humidity before the increments are calculated. After all variables have been incremented, the resulting field ($\Psi_{t+\Delta t}$) is converted back to humidity mixing ratio. Additional damping is included in the forecast model to control any unwanted oscillations which are generated. Since the interpolation is purely univariate, changes to the surface pressure and temperature fields do not directly affect the winds, and changes to the surface pressure field do not directly affect the temperature structure aloft. To assist the assimilation of the data, additional geostrophic wind increments are calculated from the surface pressure and potential temperature increments, and added to the wind field at each time-step; also, additional potential temperature increments are calculated from the surface pressure increments using the hydrostatic equation and added to the potential temperature field at each time-step.

The 'assimilation cycle' for the global model may be summarized as follows. Observations valid within 3 hours of 0600 GMT are assimilated into the 6-hour forecast starting at 0000 GMT and the resulting field is the 0600 GMT analysis. Observations valid within 3 hours of 1200 GMT are then assimilated into the 6-hour forecast starting from this 0600 GMT analysis. The process continues in a similar way for the remainder of the 24-hour period. In practice the situation is a little more complicated

as forecasts have to be run as early as possible in order to be useful. At present, therefore, the 0000 and 1200 GMT assimilations are actually performed twice, once to start the global model forecast at 0320 or 1520 GMT and once as part of the assimilation cycle at about 1130 or 2330 GMT. This repeat or 'update' assimilation is run as late as possible to allow time for extra data to be received and for CFO to carry out intervention. The update assimilation is followed immediately by the 0600 or 1800 GMT assimilation.

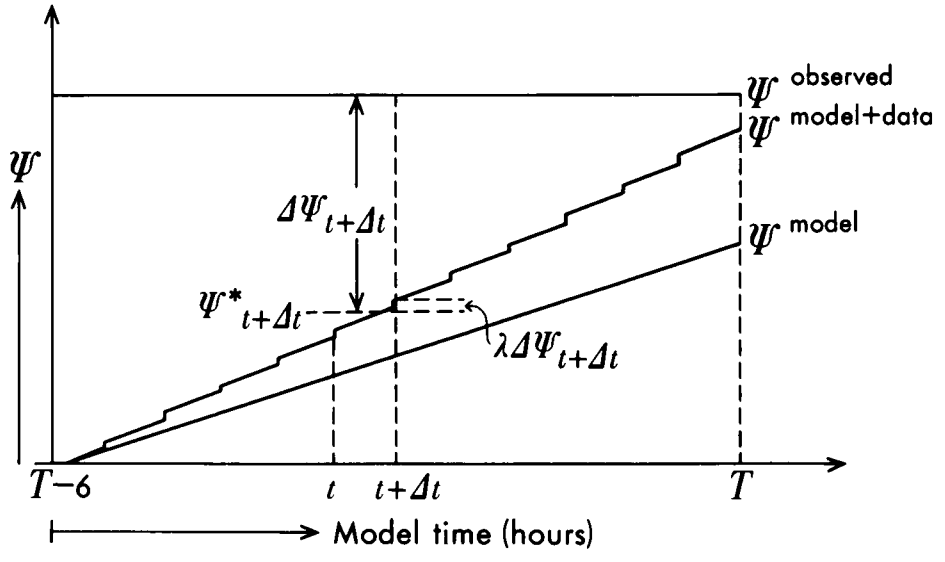

Figure 1. Schematic diagram of data assimilation. The vertical coordinate Ψ represents the state of the model or the atmosphere. The horizontal coordinate is the model time in hours. T is the validity time of the assimilation depicted and T-6 is the time of the previous assimilation. $\Psi^{observed}$ is the state of the atmosphere as determined from observations at time T. Ψ^{model} is the 6-hour forecast from the previous assimilation at time T-6. $\Psi^{model+data}$ is the result of assimilating observations for time T into the 6-hour forecast from T-6. t and $t+\Delta t$ are two successive time-steps of the forecast and $\Psi^*_{t+\Delta t}$, $\Delta\Psi_{t+\Delta t}$ and λ are as defined in the text. Note that $\Psi^{model+data}$ will not equal $\Psi^{observed}$ as allowance is made for errors in the observations.

Fine-mesh assimilation

Initial fields for the regional fine-mesh model are provided by a fine-mesh assimilation. This is based on the same principle as the global assimilation except that the assimilation is performed by the regional model at three-hourly intervals instead of six and, for each assimilation, observations within 1½ hours of the analysis time are used. Global information from observations made at earlier times is incorporated by restarting every 12 hours by interpolation from a global update assimilation, and performing 12 hours of fine-mesh assimilation at 3-hourly intervals to provide an initial field for the fine-mesh model valid at 0000 or 1200 GMT. Lateral boundary conditions for this fine-mesh assimilation are provided by a 12-hour coarse-mesh forecast from the global update assimilation. The fine-mesh assimilation scheme has therefore both a higher spatial and temporal resolution than the global assimilation scheme and this enables more detailed analyses to be made.

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Sea surface wave and storm surge models

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Summary

Numerical models for use as guidance in oceanographic forecasting have been used in the Meteorological Office for many years. The development of the present state of the art is briefly traced, with reference to the key requirements of forecasting for coastal defences and the North Sea oil industry. The present mode of use, mathematical formulation, and performance characteristics of the operational storm surge and surface wave models are separately discussed. The results of verification exercises illustrate that whereas forecasts of an acceptable accuracy are usually obtained there is still room for model development. Some possible avenues of improvement are discussed, including unification of the two continental shelf models into a single interactive system.

1. Introduction

The operational use of numerical models as an aid in forecasting for marine services has a long history in the Meteorological Office, especially if by the term 'model' we include such mathematical techniques as empirical equations based on statistical models of ocean–atmosphere relationships. Such empirical models were used in the Office for many years before the relatively recent advent of the more sophisticated models which require powerful computing resources in order to solve the basic physical equations.

Following the disastrous coastal flooding of 1953 a Storm Tide Warning Service (STWS) was set up, working closely with the Central Forecasting Office (Synnott 1964). A system of empirical forecasting equations, still in use by the STWS, was first investigated for operational use during the mid 1960s (Keers 1966); before that time much research into the technique had been carried out at the Liverpool Tidal Institute (now Institute of Oceanographic Sciences) and at other oceanographic research centres. These equations, which relate surge residual height (the difference between actual sea level and the astronomical tide) to such meteorological variables as surface pressure and wind speed, were refined during the late 1960s (Keers 1968) and early 1970s (Hunt 1972) by the inclusion of more data and by investigation into methods of representing the non-linear behaviour of the surge in the shallower waters of the southern North Sea. More recently, in 1978, a numerical model that explicitly calculates surge residuals by means of solving the relevant dynamical and physical equations was introduced operationally. This model was also developed by the Institute of Oceanographic Sciences (Flather 1981) and has proved to be of great value to the STWS in their work. The model, its development and basic theory, are described in more detail later in this paper.

The forecasting of surface wave conditions has been a major feature of the services offered by the Office since the development of the North Sea oil industry in the 1970s. Originally, forecasters at London Weather Centre made use of empirical growth curves (World Meteorological Organization 1976) to gain an estimate of likely wave heights, using forecast values of surface wind speed, direction and fetch. Similar methods were also in use to supply the Ship Routeing Service with forecast wave data for the North Atlantic. A numerical model for computing surface waves in deep water was brought into operational use in 1976, followed by a shallow-water version in 1977. Various improvements have been made to these models since that time, leading to the current status of the models which will be described later in this paper.

The output of the dynamical oceanographic models discussed here is used for a wide variety of purposes; these are discussed and illustrated in a paper to appear in the next issue (Ephraums 1985). The

models are run on the CDC Cyber 205 computer, making full use of the vector processing facilities. Results of integrations are then transferred to an IBM front-end system where post-processing is carried out in order to generate data in a form suitable for output purposes.

2. The storm surge model

(a) *General discussion*

A numerical storm surge model has been in operational use at the Meteorological Office since 1978. The model is run as part of the operational forecasting suite, following the high-resolution limited-area atmospheric model, twice a day from September to May. Effectively, forecasts for up to 33 hours ahead are produced since the model products are not available to the forecasters of the STWS until just after 3 hours past the initial data time. The area covered by the model is approximately 11°W to 11°E, 46°N to 63°N, on a latitude–longitude grid with spacing of $\frac{1}{3}° \times \frac{1}{2}°$. The North Sea and near continental shelf are well represented at this resolution, which is slightly coarser than that of the continental shelf wave model. The undisturbed water depth is specified at each grid point.

Surface wind and pressure information is written up every hour during the forecast run of the fine-mesh NWP (numerical weather prediction) model. These data are first of all converted to wind stress and effective hydrostatic pressure respectively, and then linearly interpolated from the $(\frac{3}{4}° \times \frac{15}{16}°)$ grid of the NWP model to that of the surge model. The 'surface' wind field of the NWP model is the wind from the lowest level of the model, located at approximately 25 m above sea level; the implications of using a wind at this level are examined in a later section.

Two runs of the surge model are performed in order to obtain the residual height data. In the first run the tidal predictions for each grid point are calculated using 6 tidal components. These data enable a second run to be made which includes the meteorological effects in addition to the tidal terms. The surge residuals are then obtained by subtracting the results of the purely tidal run from that which includes both tidal and meteorological terms. In this way the tide–surge interaction, which is of greatest importance in shallow water, is included in the calculations.

The initial conditions for a surge model forecast are at present taken from the results of the previous 12-hour forecast. In this way any errors due to a poor wind and pressure forecast are carried over and perpetuated. A method of avoiding such a situation is to introduce a 'hindcast' run, similar to that performed in the surface wave models (see later). Such a system has been tried in the past and proved to be worth while, and there are plans to introduce it for the present storm surge model.

(b) *Mathematical formulation*

The mathematical basis of the model is formed by the depth-integrated equations of motion and continuity. Following the most recent and comprehensive description of the operational model (Procter and Flather 1983), the complete equations are approximated by:

$$\frac{\partial \zeta}{\partial t} + \frac{1}{R\cos\phi}\left\{\frac{\partial}{\partial \lambda}(D\bar{u}) + \frac{\partial}{\partial \phi}(D\bar{v}\cos\phi)\right\} = 0 \quad \ldots\ldots\ldots\ldots\ldots (1)$$

$$\frac{\partial \bar{u}}{\partial t} + \frac{\bar{u}}{R\cos\phi}\frac{\partial \bar{u}}{\partial \lambda} + \frac{\bar{v}}{R}\frac{\partial \bar{u}}{\partial \phi} - f\bar{v} = \frac{g}{R\cos\phi}\frac{\partial}{\partial \lambda}\left[\zeta - \frac{P_a}{\rho g}\right] + \frac{F_s - F_b}{\rho D} \quad \ldots\ldots\ldots\ldots (2)$$

$$\frac{\partial \bar{v}}{\partial t} + \frac{\bar{u}}{R\cos\phi}\frac{\partial \bar{v}}{\partial \lambda} + \frac{\bar{v}}{R}\frac{\partial \bar{v}}{\partial \phi} + f\bar{u} = \frac{g}{R}\frac{\partial}{\partial \phi}\left[\zeta - \frac{P_a}{\rho g}\right] + \frac{G_s - G_b}{\rho D} \quad \ldots\ldots\ldots\ldots (3)$$

where the notation is as follows:

$f = 2\Omega\sin\phi$	the 'Coriolis' parameter;
t, λ, ϕ	time, east-longitude and latitude respectively;
$\bar{u}$, $\bar{v}$,	components of the depth mean current $\boldsymbol{q}$;
ζ	elevation of the sea surface;
h	undisturbed water depth;
$D = h + \zeta$	total water depth;
R, Ω, g, ρ	geophysical constants (earth radius, earth rotation rate, gravity, density of sea water);
P_a	atmospheric pressure at sea level;
F_s, G_s	components of wind stress τ_s on the sea surface;
F_b, G_b	components of stress on the sea bed, τ_b.

The stress on the sea bed is calculated by assuming a quadratic stress law in order to relate the stress to the depth mean current, i.e.

$$\tau_b = -0.0025\ \rho\ \boldsymbol{q}\ |\ \boldsymbol{q}\ | .$$

Similarly the surface stress is computed from the atmospheric wind data by means of the relationship

$$\tau_s = \rho_a\ 10^{-3}\ (0.63 + 0.066\ |\boldsymbol{W}|)\ \boldsymbol{W}\ |\boldsymbol{W}|$$

where ρ_a = the density of air (1.25 kg m^{-3}) and $\boldsymbol{W}$ is the surface wind.

Horizontal boundary conditions are given by assuming zero flow normal to coastlines, and by seeking to prevent artificial reflections from the open boundaries of disturbances generated within the model. The latter effect is achieved by allowing outward propagation as free progressive waves, while ensuring the generation of the tidal constituents at the boundaries. The details of the finite difference schemes adopted for the numerical integrations of equations (1)–(3) may be found in Procter and Flather (1983). By excluding very deep water areas off the continental shelf, the time-step of the integration is allowed to be fixed at 144 seconds.

(c) *Performance characteristics*

During the winter season of 1983/84 the STWS found that in general the model overpredicted positive surge residuals, especially in the southern areas of the North Sea. The data used for verification were taken from reliable tide gauges located at ports around the British coast. Some error statistics for four locations are given in Table I. The tendency for overprediction is shown by the positive mean errors, and also by the larger extreme values of over-forecasts, much larger numerically than the extreme under-forecasts. A small improvement in forecast quality with reduction in forecast period can be seen, but this is really very marginal. A possible explanation of the overestimation seen in these recent verification figures may be found in the direct use of winds taken from the lowest level of the NWP model. Traditionally, winds at 10 m above sea level have been used throughout the development of the surge model, especially in the derivation of the surface wind stress relationship (Smith and Banke 1975). It is thus possible that further modelling of the wind at the output stage, using the thermal structure of the NWP model, in order to generate winds nominally at 10 m above sea level, would be a beneficial development.

3. The surface wave model

(a) *General discussion*

The surface wave model at present run on an operational basis in the Meteorological Office is the result of an evolving series of such models, in use since 1976. Similarly to the surge model, the wave

Table I. *Error statistics of storm surge model residual estimates, winter 1983/84*

Port, and time of issue of forecast before high water		Number of cases	Root-mean-square error	Mean error *metres*	Largest errors overf'cast/underf'cast
Tyne	-12	40	0.20	+0.09	+0.48/-0.19
	-4	33	0.18	+0.04	+0.46/-0.27
Immingham	-12	39	0.23	+0.17	+0.55/-0.11
	-6	33	0.23	+0.13	+0.55/-0.33
Lowestoft	-12	30	0.44	+0.34	+0.89/-0.24
	-6	30	0.33	+0.21	+0.90/-0.33
Sheerness	-12	36	0.38	+0.22	+1.00/-0.33
	-7	24	0.31	+0.22	+0.88/-0.11

models (three versions) are driven by wind fields extracted from the operational NWP models. All models are run twice daily, but throughout the whole year rather than just in the winter season. The three versions in operational use cover different areas on different scales, and are run for different forecast periods (see Table II). The only difference in formulation between these three models is the inclusion of extra shallow-water terms in the continental shelf model. The model integrations are at present carried out on a polar stereographic grid, following the appropriate interpolation of the wind fields from the latitude–longitude grids of the NWP models. The wind input for the wave models is assumed in the basic theory to be at a height of 19.5 m, hence the use of direct lower-level winds from the NWP models is not inappropriate here as it probably is for the surge model.

Table II. *Physical specification of operational wave models in the Meteorological Office*

Model	Resolution at 60°N	Origin and frequency of wind field data	Forecast period	Depth-dependent terms
Northern hemisphere	150 km	Global NWP model, every 1½ hours	3 days	No
Continental shelf	25 km	Fine-mesh NWP model, every ½ hour	36 hours	Yes
Mediterranean	50 km	Fine-mesh NWP model, every ½ hour	36 hours	No

Unlike an NWP model, where there are sufficient observed data to allow an 'analysis' (or starting field) to be calculated for all the different variables, the wave model has to be initialized by means of a 'hindcast'. This is essentially the repeat of the first 12 hours of the previous forecast (run 12 hours ago) but this time using improved wind fields, improved by making use of the intervening analysis runs of the NWP model. There are insufficient measurements of the directional wave spectrum to allow a wave analysis and, additionally, the theoretical mathematical work on which to base such an analysis has yet to be carried out. The hindcast technique yields a series of fields, 12 hours apart, which are the best description of the actual wave fields that can at present be derived. The archive of these fields has many uses; these are discussed in a companion paper (Ephraums 1985).

(b) *Mathematical formulation*

The theoretical basis of the wave model is the representation of the wave field as a spectrum — essentially the variance of the sea surface elevations that are present in a statistically random fashion. The behaviour of individual components of the spectrum can be calculated from known theories, and the more commonly recognized quantities such as wave height and period can be calculated from

moments of the spectrum. A simple example of a directional wave spectrum is shown in Fig. 1. The model at present has 16 equally spaced directions and 14 irregularly distributed frequency values, ranging from 0.04 Hz (25 seconds period) to 0.324 Hz (≈3.1 seconds period). Thus at each model grid point 224 discrete spectral energy density values are stored.

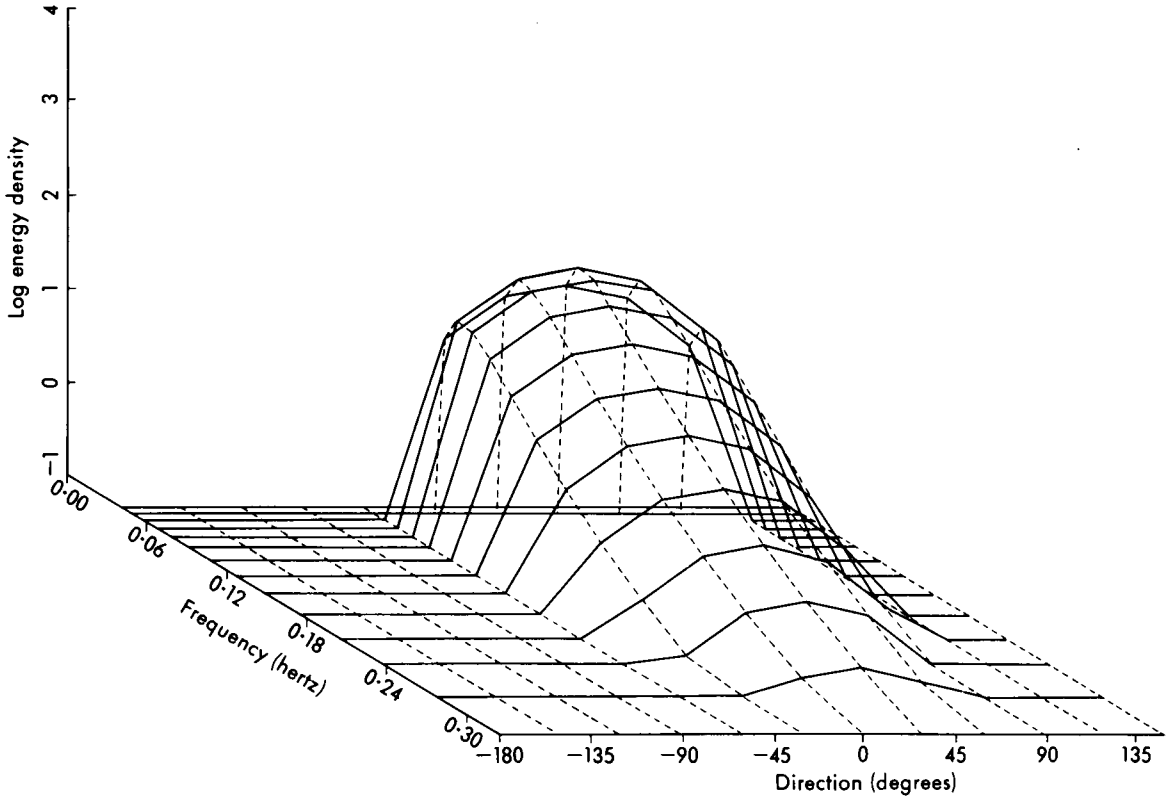

Figure 1. The limiting energy spectrum for a wind of 20 m s^{-1} from 360°.

The variation of these values in time and space is controlled by means of integrating the energy balance equation:

$$\frac{\partial E}{\partial t} + \nabla\cdot(EC_g) + \frac{\partial}{\partial\theta}\left[(C_g\cdot\nabla\theta)E\right] = S_{in} + S_{ds} + S_{nl} \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

(ADVECTION) (REFRACTION) (SOURCE/SINK)

where the following notation is used:

$E(f, \theta, x, t)$ is the energy density in a spectral component with frequency f, travelling in a direction θ, at a location x at time t;

$C_g(f, \theta)$ is the group velocity of the component (a function of depth);

S_{in} represents the energy input from the atmosphere;

S_{ds} represents energy loss; and

S_{nl} represents the internal redistribution of energy due to non-linear interactions.

Full details of the mathematical and physical theories used in the model may be found in a comprehensive paper (Golding 1983). It is sufficient here to outline the processes in a more general way.

The advection, or propagation, term is calculated by means of standard finite difference techniques, with appropriate treatment at coastal and open boundaries in order to prevent reflection. The refraction term is solved by adopting a continuous form of Snell's Law, more familiar in optics, in order to calculate the effects of irregular bottom topography on the component waves. The source and sink terms S_{in}, S_{ds} contain a number of processes which attempt to represent the currently held theories concerning wave growth and decay. In simple terms the growth of sea waves is due to the input of atmospheric energy through boundary-layer transfer processes which are still not completely understood. What is clearly apparent is that growth is inhibited by a limit on wave size and shape, beyond which breaking takes place with an accompanying loss of energy. The growth and decay processes in the model (for deep-water states) are balanced so that the limiting form is attained but not exceeded, and also so that observed growth rates are reproduced. In shallow water an extra dissipation term is introduced to represent the energy loss through frictional effects on the sea bed.

Finally, the non-linear interaction term, S_{nl}, is introduced in order that the eventual spectral shape is close to that observed in physical reality. It is known from an extensive series of measurements that the spectrum of a wind sea (i.e. that portion of the full spectral range within the influence of the local generating wind) is maintained in a recognized shape by means of internal energy transfers from high to low frequency. The calculation of the exact transfer terms is, however, at present beyond the capacity of most computing systems, especially if real-time forecasts are required. Hence we have adopted an empirical approach which assumes a spectral form, the JONSWAP spectrum (Hasselmann *et al.* 1973), and redistributes the wind sea energy, without loss, into that form. The main difficulty with this method is the problem of separating wind sea from swell (i.e. that portion of the spectrum not under the local influence of the wind) in order to generate the spectral shape, but the model results as discussed in the next section confirm that the present empirical scheme is giving an acceptable approximation to a very complex physical process.

(c) *Performance characteristics*

The wave model can be assessed in two distinct ways: firstly by comparison of values of significant wave height (approximately that height assessed by visual estimation, more specifically the mean height of the highest one-third of the waves present) as calculated by the model and as observed and reported from maritime stations; and secondly by means of comparison with measured wave data, for example that from a wave rider buoy or similar device. The first verification technique is performed operationally at Bracknell, where incoming wave data from synoptic reports are routinely compared with model results. Table III shows some error statistics from three representative stations. Ocean Weather Ship 'L' is in deep water, the oil platform Statfjord is near the edge of the continental shelf, depth about 130 m, and the platform K-13 is in the much shallower regions of the southern North Sea, depth about 30 m. Points to note from the figures in the table are:

(i) Errors grow with observed wave height, but not so markedly with forecast period.

(ii) The effects of the extra friction terms in the continental shelf model are apparent in the results for Statfjord where, although the water depth is still appreciable, the coarser-mesh model is yielding higher wave height forecasts throughout all ranges of observed height.

Details of a comparison against data from a wave rider buoy can be found in Fig. 2. The fine-mesh model has given very acceptable forecasts for a location about 500 m offshore in 13 m of water. Such a performance confirms the potential that the model has for many shallow-water applications (Ephraums 1985).

Table III. *Error statistics of significant wave height in operational wave models in the Meteorological Office, 1983 and 1984*

Station	Forecast time	Forecast model	0–3 m N	0–3 m $\bar{X}$	0–3 m σ	3–6 m N	3–6 m $\bar{X}$	3–6 m σ	>6 m N	>6 m $\bar{X}$	>6 m σ
OWS 'L'	00	NH	466	0.1	0.9	633	0.3	1.3	169	0.7	1.6
57°N, 20°W	24		467	0.1	0.9	647	0.3	1.3	178	0.7	1.9
Statfjord	00	NH	586	0.3	0.7	375	0.9	1.0	41	1.2	1.6
61.2°N, 1.8°E	24		598	0.3	0.8	380	0.9	1.2	41	1.2	1.8
	00	CS	580	0.1	0.6	371	0.6	0.8	41	0.7	0.8
	24		587	0.2	0.7	374	0.7	1.1	40	0.8	1.3
K-13	00	CS	1037	0.0	0.3	86	-0.3	0.6	0		
53.2°N, 3.2°E	24		1055	0.2	0.5	87	-0.1	0.8	0		

Wave height ranges are for observations; N = number of cases; $\bar{X}$ = mean error in metres; σ = standard deviation of error in metres; NH = northern hemisphere; CS = continental shelf.

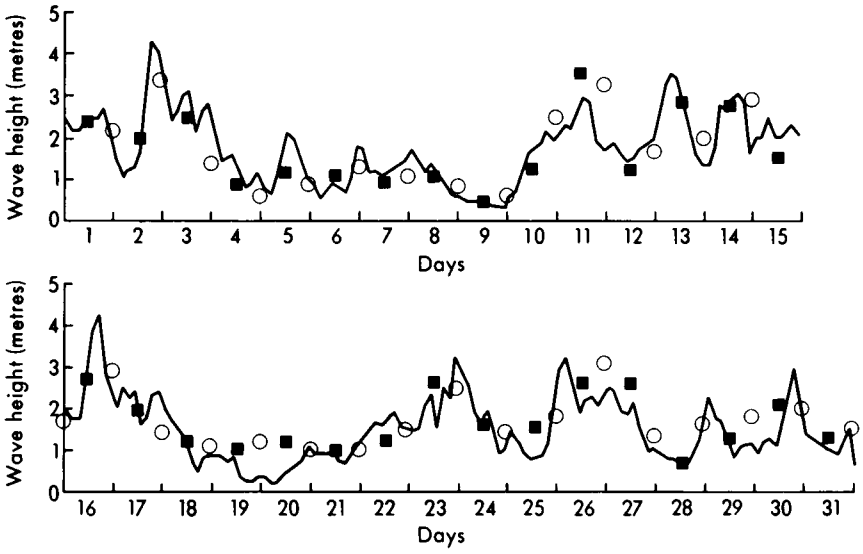

Figure 2. Comparison of wave heights, actual and forecast, for Seaford, January 1984 (by courtesy of Southern Water, and Hydraulics Research, Wallingford).
——— observed wave heights from wave rider buoy
■ ■ ■ 12-hour forecast (for 12 GMT made at 00 GMT)
○ ○ ○ 24-hour forecast (made at 00 GMT the previous night)
Forecasts at location 50.6°N, 0.8°E; Seaford wave rider buoy at 50.76°N, 0.08°E.

4. Future developments

The present situation, in which the storm surge model and the fine-mesh model are run separately, is far from satisfactory since a unified model would add far more to the accuracy of the results than just an increase in operational efficiency. The potential advantages in a unified model are threefold. Firstly, long-wave propagation is strongly influenced by water depth, hence tidal and surge influences on water

depths in areas of shallow mean water level are likely to be significant for wave forecasts. The southern North Sea is a particularly interesting area in this respect. Secondly, it is well known that currents have a marked effect on waves, and it is quite likely that the depth-integrated currents of the surge model could be used to give better wave forecasts in regions of strong tidal currents. Thirdly, the surface stress which drives the surge model is directly linked to the roughness of the sea surface. Thus a knowledge of the state of sea should result in more accurate computations of the stress input for surge modelling.

Both kinds of operational oceanographic model will benefit from the assimilation of measured data on a routine basis. For the surge model the requirement is a balanced set of current and height data; for the wave models a fairly comprehensive description of the directional spectrum is necessary. Such data are at present not readily available and it may be some years before data in large enough amounts, e.g. remotely sensed from satellites, make such an assimilation process viable. In the meantime some research work is necessary in order to solve the mathematical difficulties inherent in the process.

Research work into wave and surge modelling is at present coming to the fore in many European countries, and a joint initiative for co-ordinating further work has recently been inaugurated. The WAM group (WAve Modelling), with members from nearly all the maritime European nations, intends to address itself to the many problems that remain to be solved in order that real-time oceanographic forecasting for a variety of marine applications will achieve even better results than at present.

As part of this program the Meteorological Office is currently performing experiments with a wave model on a latitude–longitude grid, with the intention of providing a full global forecasting capability in 1986. At the same time the new model is to be used as a 'test bed' facility with which to investigate the progress of some of the work in the WAM initiative.

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Output products of the Bracknell numerical weather prediction models

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Summary

The data produced by the numerical weather prediction models are further processed in order that a comprehensive set of output products can be generated operationally. The first step is the generation of an output data set which contains both primary and derived variables, arranged on fields at constant standard pressure levels. The derived variables are those which are not explicitly contained in the forecast model data.

Charts and coded bulletins are then constructed from the output data set, using a variety of formats requested by users, and internationally agreed. Lists are provided of the current charts and code bulletins available. A discussion of back-up arrangements concludes the presentation of output products.

1. Introduction

The numerical weather prediction (NWP) models described in a companion paper (Gadd 1985) yield large amounts of data when run operationally. These data (for different variables, model grid points, model levels, forecast times) are internally arranged and represented in a form that is convenient for the rapid integration of a numerical model. Such a representation is, however, far from convenient for the production of the large quantity of output, in many forms, that is needed to satisfy the requirements of modern meteorological services. In order that a versatile range of output products can be easily generated it is first necessary to rearrange the forecast model data fields into a more suitable format. At the same time it is convenient to generate (by further modelling techniques) those fields which are not explicitly carried in the models, but which are required for operational purposes. These 'derived' fields are listed in Table I, together with the other standard formats for explicitly held variables.

The output variables, held in a comprehensive data set, are then transferred from the Cyber 205 fast vector processor to a conventional 'front-end' processor, currently an IBM 3081. After reformatting, the output data set is available for access by authorized users, as well as being the source of all the operational output data streams. A versatile suite of access routines is available which allow data to be

Table I. *Variables stored in output formats, both basic and derived*

Model variable	Basic output forms	Derived output forms
Wind	Speed and direction on standard pressure levels	Vertical velocity at standard levels. Maximum wind, height, speed, direction. Surface (10 m) wind, speed, direction. Vorticity at standard levels. Clear-air turbulence index (200, 250, 300 mb).
Temperature Surface pressure	Temperatures and heights of standard pressure levels. Mean-sea-level pressure	Tropopause temperature, pressure, height. Height and pressure of freezing level. Surface (1.5 m) temperature. Wet-bulb potential temperature (500, 850 mb).
Humidity	Relative humidity at standard pressure levels $\geqslant$500 mb.	
Precipitation	Dynamic and convective rates and accumulations.	

extracted and then interpolated on to a wide range of latitude–longitude grids, and also on to different map projections, including Polar Stereographic and Mercator. Another advantage of retaining output products on a front-end processor is the ease of communication with other computing systems, and the fact that incoming back-up data from the National Meteorological Center (NMC) in Washington DC, and the medium-range data from the European Centre for Medium Range Weather Forecasts (ECMWF) can be collected and stored in the same output format, ready for presentation in chart form using standard computer software.

2. Output modelling techniques

The first stage in the process of generating output products (Fig. 1) is the construction of a comprehensive data set which consists of the required basic and derived variables, stored on pressure levels. Table I briefly sets out the current contents of the output data set. Not all of the derived fields are generated by both versions of the NWP model (i.e. global and fine-mesh versions), but all of the basic output forms are common to both. Variables directly associated with aviation forecasting (tropopause and maximum wind, for instance) are generated only from global model data.

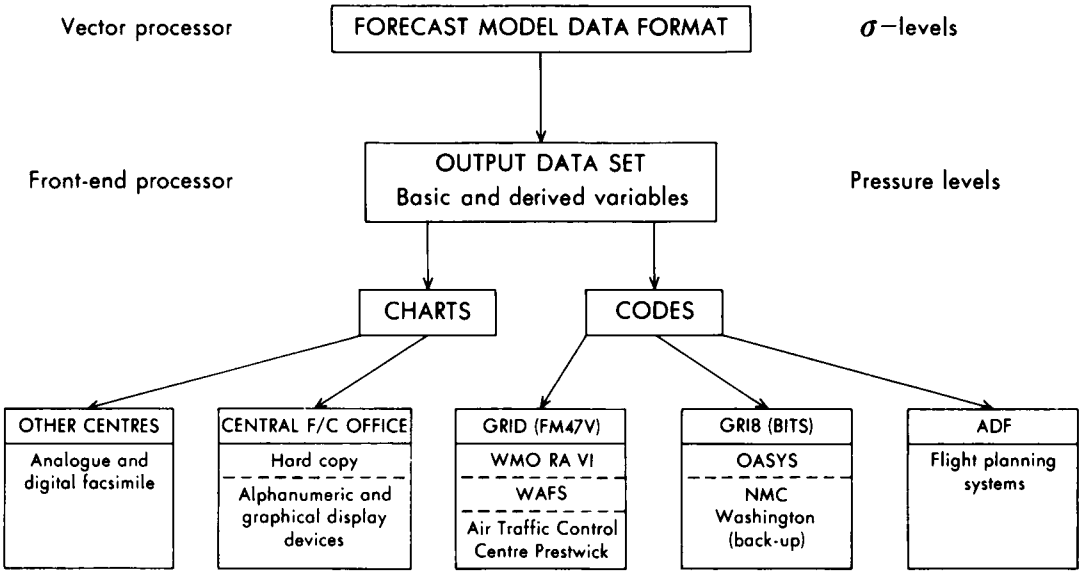

Figure 1. Organization of data set for generating output products.

(a) *Wind modelling*

The initial step in the wind modelling is the calculation of the vertical velocity. This calculation is performed while the horizontal wind components are still on σ-levels, and is carried out in a manner similar to that employed in the forecast model. Divergences at every grid point are calculated for each

model layer and summed from the top downwards. In the same manner, absolute vorticity is also calculated from the horizontal wind components, before interpolation on to pressure levels is carried out. The required interpolation, for both vertical velocity and absolute vorticity, is calculated by assuming that the variables change linearly with the logarithm of pressure, written log (pressure) below.

The next step is to calculate the speed, direction and pressure level of the maximum wind. The wind components are first combined to give a speed and direction, then a search is made for the σ-level that contains the maximum value of wind speed. The maximum of the implied continuous profile may then be assumed to lie within one model layer on either side of the designated σ-level. A cubic spline function is fitted to the wind speed values outside of the boundary layer, and by means of straightforward but detailed calculus and algebra it is possible to calculate both the profile maximum value and its level. An enhancement of the maximum value is not at present thought to be necessary since the improved definition of jet streams in the present model gives acceptable results in most situations. The direction of the maximum wind is found by means of interpolation in log (pressure) once the level has been determined.

Consistent with the vertical interpolation used for other wind parameters, wind speed and direction on standard levels are determined by assuming a linear variation with log (pressure) of the u, v components between the σ-levels. The maximum wind information is used as an extra level in order to give consistency in that region. Standard levels that fall below model orography are assigned the wind speed and direction of the lowest σ-level.

Another derived 'wind' parameter is the clear-air turbulence (CAT) index, which is calculated using the formulation established for the previous NWP model (Dutton 1980). Work on updating the formulation, using data from the new NWP model related to aircraft reports of CAT, is now under way, and should lead to improvements in the definition of this very important aviation index.

Finally in this section on wind modelling, we turn to the problem of calculating a surface wind defined as the wind at 10 m above the ground or sea surface. For many forecasting applications such a wind parameter is an essential element and it is important that realistic values are derived. The technique used during the output modelling calculations is consistent with that employed in the forecast model for representing boundary-layer effects. An integral part of the system is the calculation of a boundary-layer Richardson number, taken to be a function of wind, temperature and humidity values at the surface and lowest σ-levels. This Richardson number then determines the profiles used to evaluate both surface wind and temperature over land and over sea. The profiles vary with the implied stability in the boundary layer, and contain the implicit contributions of surface roughness length and drag coefficient. The direction of the surface wind is taken to be that of the wind in the lowest σ-level.

(b) *Temperature modelling*

The first stage in the process of calculating the heights and temperatures of standard levels is to convert the potential temperatures on σ-levels, used in the forecast model, into the associated temperature values. Then the thickness between σ-levels can be calculated using the σ-level virtual temperatures. In this way the effects of humidity on the thicknesses are included. The heights of the σ-levels can then be derived by summation of thicknesses from the lowest level upward. The temperature at each standard pressure level is calculated firstly by locating it between two σ-levels, and then by assuming a constant temperature lapse rate between those levels. The height at each standard pressure level is calculated by assuming a constant virtual temperature for the layer between the pressure level and the lower (in height) of the two reference σ-levels.

For pressure levels below the model orography it is necessary to adopt a pragmatic approach in order to obtain acceptable temperature and height values. The associated calculation of pressure at mean sea

level is performed in a consistent manner. Height values below orography are primarily required so that realistic contour charts can be produced for the forecaster. Such charts require to be smooth, and to appear as if the intruding orographic feature was not present. Accordingly it is acceptable to extrapolate from a 'free atmosphere' level in order to obtain the temperature for a subterranean standard level, thus avoiding the effects of the boundary layer. The extrapolation uses a standard lapse rate of 0.0065 K m^{-1}. The height at the subterranean standard level is obtained by subtracting the thickness of the layer between the lowest σ-level and the standard pressure level concerned, again calculated using the assumption of a constant virtual temperature throughout the layer. The pressure at mean sea level is given by an equivalent calculation using the orographic height and an extrapolated temperature profile as above. For zero orography the pressure at mean sea level is of course equal to the surface pressure.

The next task is to locate the tropopause and assign a consistent temperature and height. The essence of the method employed to do this is the assumption that the tropopause should be associated with a layer mean lapse rate of less than 0.002 K m^{-1}, at a height above that of surface inversions and other low-level temperature features. Layer mean lapse rates are therefore calculated, from the σ-level data, and a search is carried out (above 500 mb) for the relevant critical lapse rate. Having found the first layer for which the *mean* lapse rate is less than the critical value it is a straightforward algebraic task to calculate the exact σ-level for which the lapse rate equals 0.002 K m^{-1}, assuming a linear variation in the lapse rate between the mid-points of adjacent layers. Following further algebraic manipulation the temperature of the tropopause can be determined, and then in the same manner as described earlier the height can be calculated.

Three other temperature-dependent variables are also derived. The freezing level is located by searching upward through the σ-level data for the first value of temperature less than 273 K. The freezing level height is then calculated by assuming a constant lapse rate through the appropriate model layer. The technique for modelling surface parameters was outlined earlier in the discussion of wind variables. By this method a temperature at 1.5 m is modelled and made available for output. Finally, values of wet-bulb potential temperature are calculated by an iterative technique after the necessary temperature and humidity information has been transferred on to pressure levels.

(c) *Humidity and rainfall*

The forecast model produces values of humidity mixing ratio on σ-levels whereas for output purposes relative humidity on pressure levels is required. The first step in the transformation process is the calculation of saturation mixing ratio, performed by using a look-up table for saturation vapour pressure with reference to the σ-level temperature. The look-up table assumes saturation with respect to water for temperatures greater than −5 °C, and with respect to ice for temperatures less than −10 °C. For intermediate values the table has an interpolated entry between the two saturation states. The information is then at hand to be able to first calculate saturation mixing ratio and then relative humidity. Interpolation to pressure surfaces is again achieved by assuming a linear variation in log (pressure).

Rainfall information in the models is available as the result of both convective and dynamic processes, the basic parameter being an instantaneous rate. By accumulating the rates at each time step and multiplying by the appropriate constant it is also possible to derive values for dynamic and convective accumulations over a period. This calculation is performed in the forecast model. Enhancement of the grid-point convective values in order to represent possible convective activity in a fraction of a grid square is at present performed empirically; but the use of relevant information from the convective parametrization in the forecast model may lead to a more satisfactory procedure for such enhancement.

3. Chart output

The conventional presentation of most forecast products is by means of a chart, either containing isopleths of the required field or having numerical values printed on a regular grid. Chart products form a very important part of the output stream from the numerical models run at Bracknell. Including all kinds of charts, and those required for back-up purposes, nearly 1000 are produced in a 24-hour cycle. Not all of these are transmitted by facsimile broadcasts of course. Nearly half of them are for back-up purposes, i.e. for use if a later forecast run fails. Many are for use in the Central Forecasting Office and are not designed for wider dissemination. About 100 charts are prepared for facsimile broadcast in a 24-hour period, including a substantial number of hand-drawn products. These latter charts are prepared by forecasters at Bracknell, using forecast model products as a guide, along with other information such as satellite pictures and later observations. The final chart represents a 'man–machine mix', that is, a synthesis of computer speed and efficiency with human experience and intuition. Both hard-copy and visual display unit presentations are available to the forecaster at Bracknell (Fig. 1) for the preparation of hand-drawn products.

Three chart examples are shown in Fig. 2, and other examples are to be found in companion papers. The computer-drawn charts are produced on a Calcomp 1581 device, using a software package which extracts data from the comprehensive output data set (described earlier), and prepares it for either line drawing or grid plotting on a versatile range of chart areas and projections. Tables II and III summarize the charts currently available on facsimile broadcasts. The more acceptable modern method of disseminating forecast data is by means of coded broadcasts using higher speeds, which enable a wider range of data to be transmitted. This system will be discussed in the next section.

4. Coded output

(a) *Bracknell's dual role*

The Meteorological Office at Bracknell has a dual function as far as the dissemination of coded forecast data is concerned. As a Regional Meteorological Centre (RMC) for Region VI of the World Meteorological Organization (WMO), Bracknell makes available numerical analysis and forecast data covering Europe and the North Atlantic to other national meteorological centres. Acting as a World Area Forecast Centre (WAFC) of the World Area Forecast System (WAFS), initiated by the International Civil Aviation Organization (ICAO), Bracknell provides data with a global coverage, both directly to airlines and also to regional centres of the WAFS. The provision of these data requires the use of agreed code forms, so that rapid transmissions from centre to centre are achieved without confusion or ambiguity of meaning.

(b) *The code formats*

The rapid progress in telecommunication techniques, leading to high-speed lines and computer-to-computer connections, has resulted in a parallel development in the use of codes for transmitting numerical forecast data from one centre to another (Fig. 1). The most widely used code form is WMO GRID code (FM 47-V) which was devised for use on low-speed lines, using a character-based format, with relatively high overheads associated with possible output on line-printer devices. The majority of coded bulletins from Bracknell are in this format, and will remain so for the forseeable future; however, more efficient forms have been devised (see below) which should prove attractive enough for a major change in emphasis over the next five years. GRID code forms the mainstay of the network between national weather centres in Region VI.

The data required for flight planning purposes by airlines have traditionally been supplied in Aviation

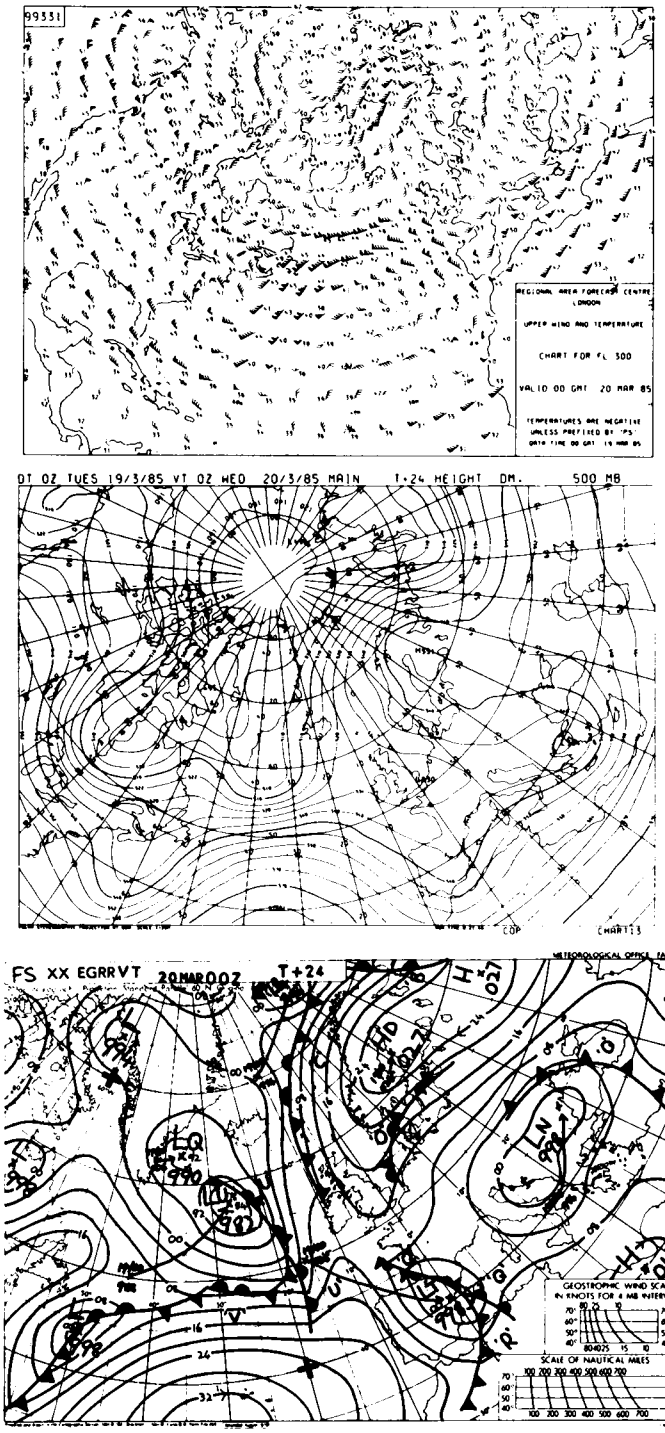
99331
REGIONAL AREA FORECAST CENTRE
LONDON
UPPER WIND AND TEMPERATURE
CHART FOR FL 500
VALID 00 GMT 20 MAR 85
TEMPERATURES ARE NEGATIVE
UNLESS PREFIXED BY "PS"
DT 0Z TUES 19/3/85 VT 0Z WED 20/3/85 MAIN T+24 HEIGHT DM. 500 MB
CHARTS
FS XX EGRRVT 20MAR00Z T+24
METEOROLOGICAL OFFICE FAX
GEOSTROPHIC WIND SCALE
IN KNOTS FOR 4 MB INTERVALS
SCALE OF NAUTICAL MILES

Figure 2. Examples of forecast charts.

Table II. *List of available chart products using Analogue Facsimile transmissions*

In the following tables all the computer-produced charts are based on data from the global numerical weather prediction model. Most of the subjectively drawn charts (M) are also largely based on the products of the same model or its derivatives.

(a) *Analysis products*

Field identifier	Reference time (GMT) and area of coverage (see Table III) 00	06	12	18	Method of production (Machine contours — C, Manual input — M)
Surface pressure, with front and centres	F D	F	F	F	M M
850, 700, 500, 300, 200 and 100 mb contours, and 500–1000 mb thickness	A		A		C
500 mb contours	D				M
500 mb contours and 500–1000 mb thickness	H		H		C
Sea surface temperature	M				M
Sea ice			E		M
State of sea	G		G		M

(b) *Forecast products*

	Data time	Validity time (hours after data time) and area of coverage (see Table III) 18	24	48	72	96	120	Method of production (Machine contours — C, Grid data — G, Manual input — M)
Surface pressure, with fronts and centres	00		F	C	C			M
	06		F					M
	12		F	C	C	C	C	M
	18		F					M
850, 700, 500, 300, 200 and 100 mb contours	00		A					C
	12		A					C
500–1000 mb thickness	00		A					C
	12		A					C
Winds and temperatures (DDFFFTT) at 850, 700, 500, 400, 300, 250 and 200 mb	00	K	K					G
	12	K	K					G
Winds and temperatures (DDFFFTT) at 500, 300, 250 and 200 mb	00	B	B					G
	12	B	B					G
Significant weather (jets, tropopause, CAT, etc.)	00	B						M
	06	B						M
	12	B						M
	18	B						M
State of sea (wave height, direction)	00		G					M
	12		G					M

Table III. *Bracknell (Regional Meteorological Centre) — list of chart areas. The projection used for all of these charts is Polar Stereographic.*

Code letter	Area				Scale in millionths
A	(48°N, 145°W)	(32°N, 68°E)	(18°N, 12°E)	(28°N, 71°W)	1:20
B	(28°N, 145°W)	(24°N, 54°E)	(09°N, 05°W)	(02°N, 84°W)	1:20
C	(42°N, 90°W)	(66°N, 90°E)	(30°N, 20°E)	(20°N, 40°W)	1:30
D	(29°N, 155°W)	(28°N, 63°E)	(08°N, 06°W)	(08°N, 85°W)	1:30
E	(57°N, 96°W)	(71°N, 71°E)	(46°N, 14°E)	(38°N, 48°W)	1:10
F	(69°N, 111°W)	(37°N, 50°E)	(19°N, 10°E)	(34°N, 55°W)	1:20
G	(42°N, 112°W)	(60°N, 32°E)	(28°N, 10°W)	(21°N, 74°W)	1:20
H	(80°N, 05°W)	(44°N, 32°E)	(28°N, 05°W)	(43°N, 41°W)	1:20
K	(53°N, 50°W)	(53°N, 65°E)	(26°N, 34°E)	(26°N, 18°W)	1:17
L	(31°N, 20°W)	(23°N, 150°E)	(06°S, 102°E)	(05°S, 33°E)	1:36
M	(67°N, 37°W)	(70°N, 18°E)	(47°N, 07°E)	(45°N, 19°W)	1:5

Digital Forecast (ADF) code. ADF was designed for a specific purpose and thus differs from GRID code (and its successors) in that the data are arranged in columns rather than in horizontal fields. The code uses a 'packed-decimal' format, i.e. more efficient than GRID code, but is still character based and thus carries a large overhead penalty. Bracknell currently provides forecast data in this code form to British Airways, Scandinavian Airlines System, and the Société Internationale de Télécommunications Aéronautiques.

In order to exchange the very large amounts of data required for the operation of the WAFS it was necessary for a much more efficient code form to be devised. As an interim measure Bracknell and the National Meteorological Center in Washington developed a bit-orientated code form, H code, which was implemented between the two centres in 1984. Subsequently WMO extended and developed the concept; a more widely agreed bit-orientated code, GRIB (GRIdded Binary), was ready for use at Bracknell from 1 January 1985, and the complete switch-over from H code took place in April 1985. This bit-orientated code has been designed for use on fully automated computer-to-computer systems and is compatible with the more efficient telecommunication protocols required for transmission on high-speed lines. The supply of data from Bracknell to automated systems (OASYS) at London Weather Centre and Heathrow Airport is an example of this computer-to-computer facility. The major part of the Bracknell coded products list is now available in GRIB code.

(c) *Products available in code*

Table IV contains a concise summary of the products that are currently available in coded form from Bracknell. Three distinct classes of product are identified: those taken from the fine-mesh NWP model, primarily for use in WMO Region VI; regional products from the global coarse-mesh NWP model, again for use in Region VI and extending into the medium range; and global products from the coarse-mesh model, formulated primarily for use in the WAFS but also available for supply to other interested users. Details of the elements contained in the bulletins, areas covered, bulletin resolution and forecast times are all to be found in Table IV.

The most recent additions to this list of products are the very-high-resolution ($1\frac{1}{4}° \times 1\frac{1}{4}°$, every 3 hours) bulletins taken from fine-mesh NWP model data. The Royal Netherlands Meteorological Institute requested such data for input to a scheme being developed for forecasting of maritime weather and state of sea conditions along the Dutch coast. Other recent requests for data, which have been met by bulletins from the extensive range available at Bracknell, came from Zimbabwe, Mauritius, Hong Kong and the Seychelles.

Table IV. *List of available forecast fields from Bracknell.*

Forecast runs are made from both 00 and 12 GMT data time. Bulletins are coded in WMO GRID (FM 47-V). Details of bulletin headings and contents can be supplied on request, including details of GRIB-code bulletins.

	Regional fine-mesh products	Regional coarse-mesh products	Global coarse-mesh products
Elements	Surface pressure, surface wind (10 m), accumulated precipitation. Heights, winds and temperatures for 850 and 500 mb.	Surface pressure, surface wind (10 m). Heights, winds and temperatures at 850, 700, 500, 400, 300, 250, 200, 150, 100 mb.	Surface pressure, surface wind (10 m), 500 mb height. Maximum wind and tropopause. Winds and temperatures at 850, 700, 500, 400, 300, 250, 200, 150, 100 mb.
Areas	The 3 areas all span 32½°N to 75°N. The longitudes covered are 70°W to 35°W (area W or 255), 35°W to 0° (area X or 256), 0° to 35°E (area Y or 257).	There are 5 areas. Four span 25°N to 75°N; the longitudes are 90°W to 45°W (area Z or 205), 45°W to 0° (area N or 206), 0° to 45°E (area O or 207), 45°E to 90°E (area P or 208). The fifth area (area I or 201) covers 75°N to 90°N and 90°W to 90°E.	There are 16 areas. In each hemisphere there are two polar areas covering latitudes 70° to 80° and 80° to 90° and 4 mid-latitude areas spanning 20° to 70° in quadrants. A further 4 areas spanning 20°N to 20°S cover the tropical belt.
Resolution	The data are normally supplied on a latitude–longitude grid at 2½° resolution. 1¼° resolution is available if required for fields of surface pressure, wind and precipitation.	The data are supplied on a latitude–longitude grid with a 2½° resolution. For the polar area (area 201), the resolution is 2½° latitude by 10° longitude.	The mid-latitude areas are at a resolution of 2½° latitude by 5° longitude; the tropical belt is at 5° latitude by 5° longitude. In the polar regions there is reduced longitudinal resolution.
Forecast times	Fields are available at 6-hour intervals from the analysis (T+0) to a forecast time of T+36. Fields of surface pressure, wind and precipitation are available at 3-hour intervals on the finer grid.	Fields are available at the following forecast times: T+0, T+6, T+12, T+18, T+24, T+30, T+36, T+42, T+48, T+60, and T+72. In addition, surface pressure and 500 mb height are available at T+96 and T+120.	Fields are available at 6-hour intervals from the analysis (T+0) to a forecast time of T+48. In addition surface pressure and 500 mb height are available at T+60, T+72, T+96, and T+120.

5. Back-up arrangements

Although modern computing systems are very reliable and have operational performance figures that approach 100% it is still inevitable that occasions will arise when the computing facilities at Bracknell, especially the Cyber 205 used for running the numerical models, are non-operational. At such times there is a need for reliable back-up arrangements, so that both chart and coded products can be supplied to the user without noticeable interruption. A computer outage of less than 12 hours is covered by ensuring that forecast data (in required formats) are routinely prepared for a period of 12 hours beyond that normally required. By storing the data on the front-end processing system it is then possible to supply operational users on the basis of a 12-hour-old forecast run without the users becoming aware of it.

To ensure coverage beyond 12 hours there is a mutual exchange of global forecast data between Bracknell and Washington, using GRIB code as a medium. Data from Washington arrive at Bracknell too late to be used operationally in real time, but after decoding and storage in a compatible output data set they can be used to give an almost complete range of products, although again from a 12-hour-old forecast run.

The obvious omissions from the product list when operating in a back-up mode are those from the fine-mesh NWP model. Although in the recent past it has proved possible to run versions of the previous Bracknell NWP model on the front-end processors, this is now considered to be increasingly unsatisfactory and other sources of high-resolution forecast data are required. It is possible that other members of Revion VI will be able to supply such data for back-up purposes.

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